ASURA/FDPS — Simulation of Galaxy Formation on the supercomputer Fugaku

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Talk plan

1. The current status and limiting factor of the Galaxy formation simulation
2. The new algorithm
3. Implementation on Fugaku
4. Current status
5. Future plan

The current status and limiting factor of the Galaxy formation simulation

Saitoh et al. 2019 Animation
Dark Matter: 13M, Gas (final) 3.5M, Stars: 1.9M
animation

What we do here

1. start from early universe (uniform + density perturbation + linear growth). Perform dark-matter-only simulation Example of DM-only calculation
2. Select the regions which will be galaxies, trace them back to the initial time
3. Increase the mass resolution and add gas particle, and perform the simulation again
4. Gravity, hydrodynamics, radiative transfer (simplified), star formation, supernova explosion are taken into account
5. Heating due to young and massive stars (UV feedback) is also taken into account

Inhomogeneity and timescale problem

- Gas in the galactic disk is dynamically (self-gravity) and thermally unstable
- Cool gas cools further, and become unstable against small-scale density perturbation, and eventually form stars
- Radiative heating from formed stars and energy input from Type II supernovae work as negative feedback for the cooling and star formation.
- Gas density variation: 10^{-4} to 10^{4} (cm^{-3}), temperature variation: 10 to 10^{8} (K)
- Hottest gas: supernova explosion shell

Timescale of supernova explosion shell

(Saitoh and Makino 2010, PASJ 64, 301)

$$\frac{\tau_{\rm SN}}{\tau_{\rm ISM}} = \frac{c_{\rm SN}}{c_{\rm ISM}} \propto \sqrt{\frac{T_{\rm SNe}}{T_{\rm ISM}}} \propto E_{\rm SN}^{-1/2} m^{1/2} T_{\rm ISM}^{1/2}$$

τ: timescale, c: sound speed, T: temperature,
ISM: interstellar matter, SN: supernova
$E_{\rm SN}$: Energy input from SN, m: mass resolution

With $m \sim 1 M_\odot$ (solar mass), This factor becomes around 10^4

Timescale problem

- Supernova occurs once in every 100-1000 years
- Expanding shell requires the timestep to go down to 1-10 years while other region can be integrated with 10^4-10^5 years
- With low mass resolution (current typical value is 10^4 solar mass) this problem is much less severe.

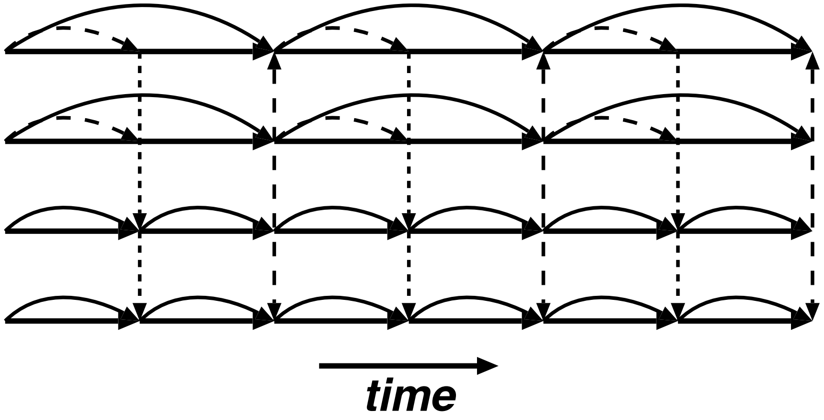
The state of the art

Project	$N_{\rm gas}$	$m_{\rm gas}$ [$M_\odot$]	$\epsilon_{\rm gas}$ [pc]	ISM model
FIRE-2 (m12i)	10^7	7×10^3	0.38(adaptive)	Full range ISM
NIHAO(g2.79e12)	10^6	3×10^5	398	Full range ISM
Eris	10^7	2×10^4	120	Full range ISM
Auriga	10^7	6×10^3	184	Two phase model
APOSTLE (L1)	10^7	1×10^4	770	$T > 10^4$ K+P floor

$N_{\rm gas}\sim10^7$, $m_{\rm gas}\sim10^4 M_\odot$,
10^5 times smaller compared to DM-only simulations

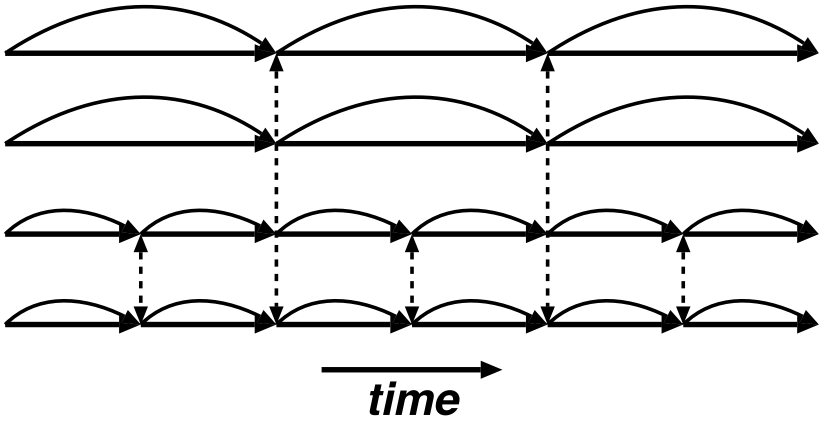
The limiting factor

Individual timestep algorithm
(blockstep, McMillan 1986, Hernquist and Katz 1989)



Each particle has its own timestep (quantized to 2^{-k})
Particles with $t_i + \Delta t_i = t_{\mathrm{now}}$ are integrated.
Other particles are predicted, and Barnes-Hut tree is constructed.
Tree construction cost (and communication overhead in the case of parallel code) dominates.

The new algorithm



Most particles are integrated with "global" timestep
Region(s) which require short timestep (or will require during the current step) are identified and integrated to new global time without interacting with the rest of the system

Based on "Hamiltonian Splitting" similar to Wisdom and Holman (1991), Skeel and Biesiadeck (1994), Chambers (1999)

Regions with short timescales are assigned to separate processor group (MPI communicator)

Both of global system and small regions are parallelized using FDPS framework

Implementation on Fugaku

- Based on FDPS framework
- Interaction kernels are generated from high-level description using PIKG (Nomura et al. in prep.)

Current status

- (more or less) working
- Efficiency is not very high yet (3-5% of peak)
- Scalability is reasonable.
- Kernel efficiency is OK (20-30% of theoretical peak for mixed-precision kernel)
- With 1/10 of Fugaku, a run with gas particle resolution of 10 $M_\odot$ would take two weeks. The resolution would be 10^3 times better than the current state of the art.

Future plan

- **Improve the performance of communications part (replace alltoallv with more optimized code)**
- **Adopt periodic boundary, implement TreePM or PM^3 (Particle-Mesh Multipole Method)**

Summary

- The number of particles used for galaxy formation simulations have been around 10M particles and have not increased much in the last two decades.
- This is in sharp contrast with dark-matter only simulations, for which 10^{12} particles can be used regularly
- The limiting factor is that the range of the timescale becomes wider for high-resolution run, resulting in the quick decrease in the parallel efficiency.
- We have developed a new algorithm which removes this bottleneck
- The code based on this new algorithm on Fugaku shows good scalability and allows us to use $> 10G$ particles within practical machine time.